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TRECOM TECHNICAL REPORT 63-70

IMPERVIOUS TURBULENT BOUNDARY LAYER MEASUREMENTS USING AN INTEGRATING BOUNDARY LAYER MOUSE

Task 1D121401A14203
Contract DA 44-177-AMC-892(T)

November 1963

prepared by:

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The study represented by this report was conducted in an attempt to devise a system whereby turbulent boundary layer data could be more readily obtained and interpreted into usable parameters. Specifically, the investigation concentrated on the use of a single composite boundary layer mouse to simplify data recording and computation. Results from the laboratory investigation indicated that the composite boundary layer mouse provided measurements well within experimental accuracy of standard boundary layer velocity profile measurements.

It was concluded that although the composite integrating mouse would not replace the usual velocity profile measuring systems, it would significantly add to the methodology of boundary layer research.

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IMPERVIOUS TURBULENT BOUNDARY LAYER MEASUREMENTS USING AN INTEGRATING BOUNDARY LAYER MOUSE

Aerophysics Research Note No. 17

Prepared by
The Aerophysics Department
Mississippi State University
State College, Mississippi

for
U. S. ARMY TRANSPORTATION RESEARCH COMMAND
FORT EUSTIS, VIRGINIA

CONTENTS

SYMBOLS

x, y	Co-ordinates
H	Total head
p	Static pressure
h	Height of integrating rake
ρ	Density
δ	Boundary layer thickness
δ^*	Displacement thickness
ν	Kinematic viscosity
θ	Momentum loss thickness
H	Boundary layer parameter
K_τ	Preston tube calibration constant
U_τ	Friction velocity
τ_o	Surface shearing stress
R_θ	Reynolds number
U_w	Velocity component due to wake
$R_{\delta^*+\theta}$	Reynolds number
σ	$= \frac{\rho}{\rho_o}$

Subscripts

∞	Freestream conditions
o	Conditions at sea level
L	Local conditions at outer edge of boundary layer

ILLUSTRATIONS

INTRODUCTION

To obtain the parameters which describe a turbulent boundary layer, it is usual to measure the boundary layer velocity profile from which can be computed, using standard techniques, such parameters as the momentum loss thickness, displacement thickness, and the surface shear. The velocity profile can be obtained using either a multitube total head "mouse" connected to a multitube water manometer or a single Pitot-static system connected to an airspeed indicator which can be raised above the surface by a calibrated micrometer screw. The former method tends to be inaccurate because of the limitations on the number of tubes and the difficulties of measuring the 'y' value accurately, and the latter method is really applicable only to wind tunnel testing where the test surface is the tunnel wall. An externally mounted screw arrangement can be fixed to the test surface; but the time taken to obtain a single profile is appreciable, and also the corrections due to the presence of the traversing mechanism on the test surface may have to be taken into consideration. The process of obtaining the boundary layer parameters from the velocity profiles is slow if performed by hand computation or expensive if programmed for a digital computer. In either case, the complete test program is slowed down due to the time lag between the experiments and the finished results.

This report deals with an attempt at devising a system for determining the turbulent boundary layer data using a single composite boundary layer mouse, which requires simultaneous reading of three airspeed indicators and from which all pertinent parameters of the boundary layer can be easily and simply computed, thereby reducing both testing and data reduction time.

THEORETICAL DEVELOPMENT OF COMPOSITE SYSTEM

It is known that if three quantities of a boundary layer on an impervious surface are known, then the remaining quantities can be found from predetermined relationships. The difficulty of obtaining one reading which is proportional to either velocity defect or momentum loss over the entire boundary layer thickness may be overcome by using an integrating boundary layer mouse connected against the local total head (Figure 2) such that

$$\Delta p = \frac{1}{h}\int_0^h (H_L - H)\,dy$$

$$\text{IF } h > \delta \text{ THEN } (H_L - H) = 0$$

$$\Delta p = \frac{1}{h}\int_0^\infty (H_L - H)\,dy$$

$$\therefore \Delta p = \int_0^\infty \left(p_L + \frac{1}{2}\rho U_L^2 - p - \frac{1}{2}\rho U^2\right) dy .$$

Assuming that the static pressure is constant through the boundary layer and that the flow is incompressible, then $p = p_L$ and $\rho = \rho_L$.

$$\therefore \Delta p = \frac{\rho}{2h}\int_0^\infty (U^2 - u^2)\,dy$$

$$= \frac{\rho}{2h}\int_0^\infty \left[U(U-u) + u(U-u)\right] dy$$

$$= \frac{\rho U^2}{2h}\int_0^\infty \left[\left(1 - \frac{u}{U}\right) + \frac{u}{U}\left(1 - \frac{u}{U}\right)\right] dy$$

$$= \frac{\rho U^2}{2h}\left(\delta^* + \theta\right)$$

As Δp is measured using an airspeed indicator (m.p.h.), then

$$\Delta p = \frac{1}{2} \rho (1.467 \, U_1)^2 . \tag{i}$$

Therefore $\quad \rho_o (1.467 U_1)^2 = \frac{\rho U^2}{h} (\delta^* + \theta)$

and $\quad U_1{}^2 = \left(\frac{\rho}{\rho_o}\right)\left(\frac{U^2}{h}\right)\frac{(\delta^* + \theta)}{(1.467)^2} .$

A local freestream Pitot-static system (Figure 2) can be used such that

$$U_2 = \frac{U}{1.467} \tag{ii}$$

Also, a calibrated Preston tube surface shear meter will give U_3 where

$$U_3 = \frac{1}{K_T} U_\tau . \tag{iii}$$

K_T is a function of diameter ratios, altitude, density, and boundary thickness. Curves of U_3 against U_τ for various altitudes appropriate for a particular Preston tube have been calculated and drawn in Figure 3. Then

$$(\delta^* + \theta) = \frac{h}{\sigma}\left(\frac{U_1}{U_2}\right)^2 \quad \text{WHERE } \sigma = \frac{\rho}{\rho_o}$$

and

$$R(\delta^* + \theta) = \frac{(\delta^* + \theta) U}{\nu} = \frac{h}{\sigma} \, \frac{1.467}{\nu} \, \frac{U_1{}^2}{U_2} ; \tag{iv}$$

also

$$\frac{U_\tau}{U} = \frac{K_T U_3}{1.467 U_2} . \tag{v}$$

Knowing $R(\delta^* + \theta)$ and $\frac{U_\tau}{U}$, $\frac{U_w}{U}$ can be obtained from Figure 4, which is a plot of the following equations from Reference 1.

$$R_{(\delta^* + \theta)} = \left[\log^{-1}\left(\frac{U}{U_\tau} - \frac{U_w}{U_\tau} - 5.6\right)\right]\left[\left(4.604 + \frac{U_w}{U_\tau}\right) - \frac{U_\tau}{U}\left(11.12 + 3.78\frac{U_w}{U_\tau} + 0.379\frac{U_w^2}{U_\tau^2}\right)\right] \quad \text{(vi)}$$

$$R_\theta = \left[\log^{-1}\left(\frac{U}{U_\tau} - \frac{U_w}{U_\tau} - 5.6\right)\right]\left[\left(2.302 + 0.5\frac{U_w}{U_\tau}\right) - \frac{U_\tau}{U}\left(11.12 + 3.78\frac{U_w}{U_\tau} + 0.379\frac{U_w^2}{U_\tau^2}\right)\right] \quad \text{(vii)}$$

Hence, using $\frac{U_\tau}{U}$ and $\frac{U_w}{U_\tau}$, R_θ can also be found from Figure 4, from which θ and, together with equation iv, δ^* can be determined.

δ, if needed, can be calculated using the following equation from Reference 1.

$$\delta = \frac{\nu}{U_\tau} \log^{-1}\left[\frac{1}{5.6}\left(\frac{U}{U_\tau} - \frac{U_w}{U_\tau}\right)\right] \quad \text{(viii)}$$

This means that all the following quantities about the boundary layer are known.

U, δ, δ^*, θ, H, R_θ, U_τ AND U_w

Similarly, if the integrating system is connected against the local static pressure instead of the total head, then

$$\Delta p = \frac{1}{h}\int_0^\infty (H - P_L)\, dy$$

$$= \frac{1}{2}\rho \frac{1}{h}\int_0^\infty u^2\, dy$$

$$= -\frac{\rho}{2h}\int_0^\infty (U^2 - u^2 - U^2)\, dy$$

$$= -\frac{\rho}{2h}\int_0^\infty \left[U(U-u) + u(U-u) - U^2\right] dy$$

$$= -\frac{\rho U^2}{2h}\int_0^\infty \left[\left(1-\frac{u}{U}\right)+\frac{u}{U}\left(1-\frac{u}{U}\right)-1\right]dy$$

$$= -\frac{\rho U^2}{2h}\left(\delta^*+\theta-h\right)$$

$$\therefore \frac{1}{2}\rho\left(1.467U_1\right)^2 = -\frac{\rho U^2}{2h}\left(\delta^*+\theta-h\right)$$

$$U_1^2 = -\left(\frac{\rho}{\rho_0}\right)\frac{U^2}{(1.467)^2}\frac{\left(\delta^*+\theta-h\right)}{h} \tag{ix}$$

as in previous case

$$U_2 \quad \frac{U}{1.467} \tag{ii}$$

and

$$U_2 = \frac{U_\tau}{K_T} \tag{iii}$$

giving

$$R_{\delta^*+\theta} = \frac{1.467\, U_2 h}{\nu}\left[1 - \frac{1}{\sigma}\left(\frac{U_1}{U_2}\right)^2\right]. \tag{x}$$

The remaining unknowns are calculated as in the previous case.

DESCRIPTION OF APPARATUS AND EXPERIMENTAL TECHNIQUES

The composite boundary layer mouse consists of fifty equally spaced total head tubes over a total range of 2.44 inches. Above the integrating rake, two total head tubes were fixed which sensed the local freestream total head; two static pressure taps and a calibrated Preston tube were on the bottom of the rake, with the Preston tube touching the surface during the tests. The integrating rake could be connected against either the local static pressure or the local total head. The equations for both methods were developed in the previous chapter. The local static pressure was connected against the freestream total head and the Preston tube, and lightly damped Kollsman helicopter airspeed indicators were used to measure the pressure differences. Great care was taken to balance dynamically all the systems of the composite boundary layer mouse for rate of change of pressure.

To check the results using this composite system, the boundary layer velocity profiles were measured by use of the standard multitube boundary layer mouse connected to a multitube photographic water manometer, and the boundary layer parameters were determined by hand computation. The comparison results are presented in graphical form in Figures 7, 8, 9, and 10.

The tests were performed on a fiberglass test section on the port wing of a Schweitzer TG-3 sailplane. The comparison tests were carried out on different chordwise stations of the section at different aircraft airspeeds, simulating various pressure gradients and boundary layer thicknesses. The maximum altitude range of the tests was from 5,000 feet to sea level in smooth turbulence-free air with a maximum Reynolds number variation of two per cent. The airspeed indicator readings together with pressure altitude and outside air temperature were radioed to the ground during the tests.

DISCUSSION OF RESULTS

The composite boundary layer mouse is well suited to aircraft and wind tunnel use if care is taken to ensure that the Preston tube touches the surface and that the tubes of the integrating rake are evenly spaced. Adequate adjustment was available by means of the rear supporting arm to always maintain the plane of measurement perpendicular to the surface, irrespective of airfoil curvature. Preliminary experiments were performed using a common static source for both the local total head and the Preston tube, but the integrating effect of this common static source gave very misleading results and an additional static source was mounted on the mouse. Great care in dynamically balancing the three systems is necessary to prevent errors due to rate of change of pressure that are associated with experiments on sailplanes.

The results obtained using the composite mouse agreed remarkably well with those obtained using the multitube mouse, the maximum differences being of the order of 5 per cent in the case of U_τ and about 4 per cent in the measurement of δ , δ^* and θ . It must be emphasized that these differences are within the experimental errors associated with using a multitube mouse and a photographic water manometer to obtain boundary layer velocity profiles. It can be seen that as the boundary layer thickness decreases, the errors in the δ^* and θ results tend to increase, which is to be expected because of the decrease in sensitivity of the integrating rake with decrease in boundary layer thickness.

The maximum error is in the determination of the skin friction velocity; and as this was measured using a Preston total head tube, some doubt must be cast upon this method of determining skin friction. Nevertheless, the accuracy is adequate to use U_τ in equation (iv) to obtain from the chart the values of δ^* and θ . It would appear that U_τ is a weak function in the boundary layer equations to obtain R_θ and $R_{\delta^*+\theta}$. An alternative method of finding U_τ is to insert the experimental values of U , θ and H , which are within 4 per cent of those obtained using the profile techniques, into the shear relationship by Ludweig and Tillmann.

$$\left(\frac{U_\tau}{U}\right)^2 = \frac{0.123}{\left(\frac{U\theta}{\nu}\right)^{.260} 10^{.678H}} \qquad \text{(xi)}$$

U_τ was calculated using equation xi for both the 75 per cent and the 85 per cent chord positions and plotted in Figures 9 and 10. The Ludweig and Tillmann results fall below those of the profile method,

indicating that the Preston tube results may be in error by as much as 12 per cent. This means that to obtain very accurate values of U_τ, θ and H are found from the composite mouse and then inserted into the Ludweig and Tillmann shear relationship.

Using the composite boundary layer mouse, it was quite usual for the values of δ^*, θ and H to be calculated and plotted while the aircraft was descending from the test altitude, whereupon the results were presented to the test engineer immediately on landing. This system enabled the plotting of pertinent turbulent boundary layer parameters over a total section to be obtained in a very short time with continual monitoring of the results.

CONCLUSIONS

The composite boundary layer mouse was found to be a very accurate and convenient instrument to use in flight experiments to determine turbulent boundary layer parameters on an impervious surface. The system could be used in wind tunnel testing, but it would be necessary to decrease the height of the integrating rake to increase the sensitivity for the thin boundary layers associated with small wind tunnel experiments.

The accuracy of the system in comparison with the profile method was well within the experimental tolerances usual with the measurement of boundary layer velocity profiles. The skin friction results obtained using the Preston shear meter were not quite so accurate, but this deficiency could be overcome by using the Ludweig and Tillmann shear relationship to obtain U_τ.

The use of the composite system simplified the data reduction which could be performed by any computer, reduced the data reduction time, and thereby appreciably speeded up the entire research program.

As a large number of turbulent boundary layer theories attempt to predict the mean velocity profile of a turbulent layer, and as these theories must be verified, the composite integrating mouse which cannot perform this task can never completely replace velocity profile measuring systems. Nevertheless, it can be used as a powerful tool in boundary layer research.

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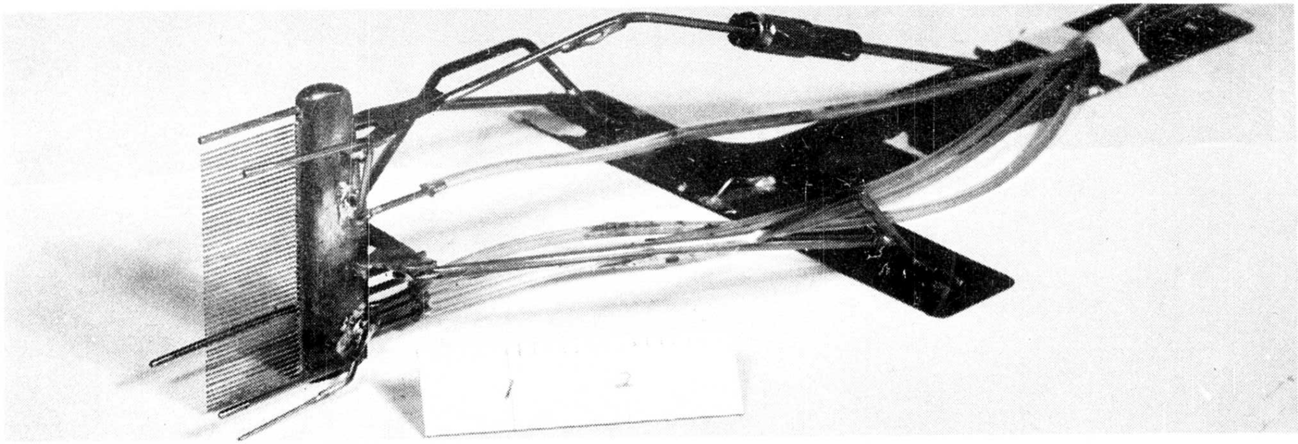

Figure 1. Composite Boundary Layer Mouse.

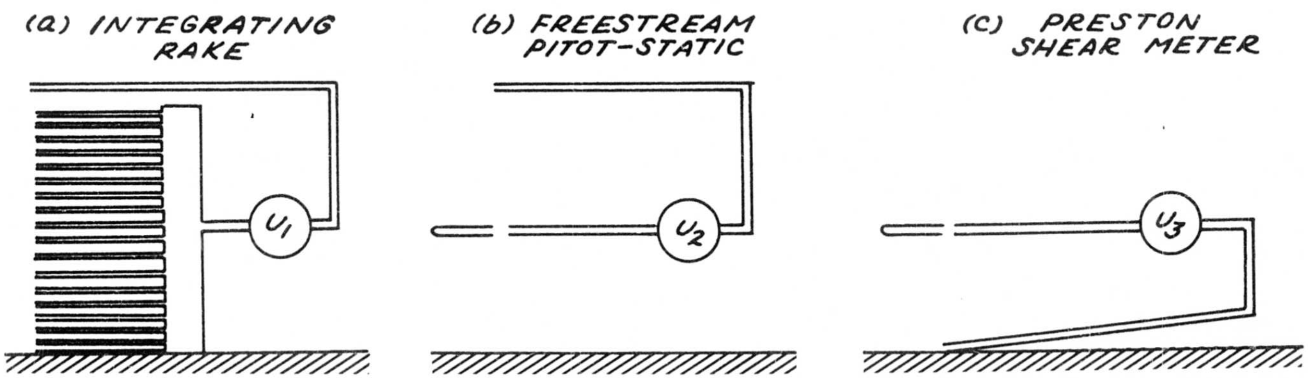

Figure 2. Diagrammatic Layout of Composite System.

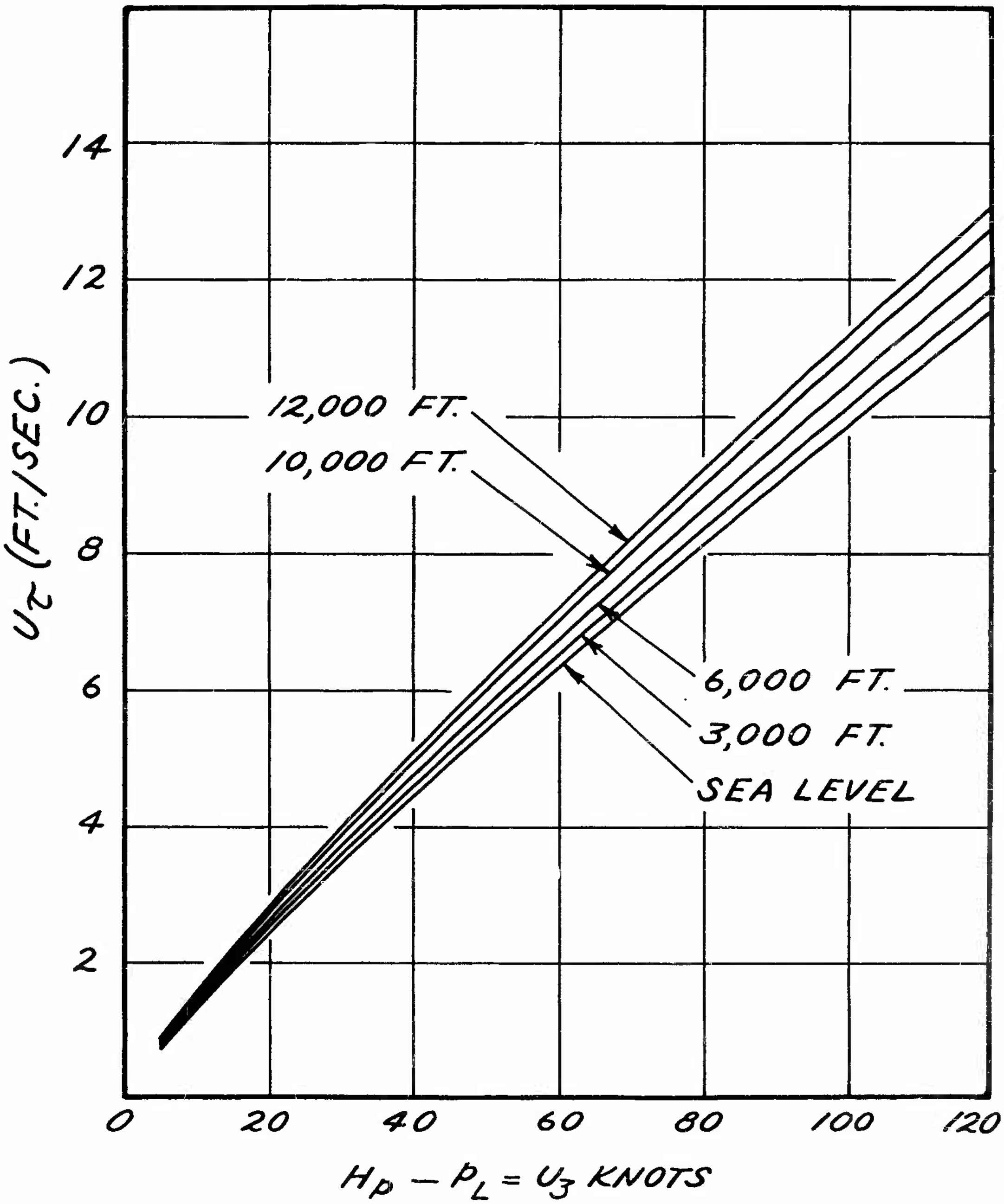

Figure 3. Preston Tube Calibration Curves.

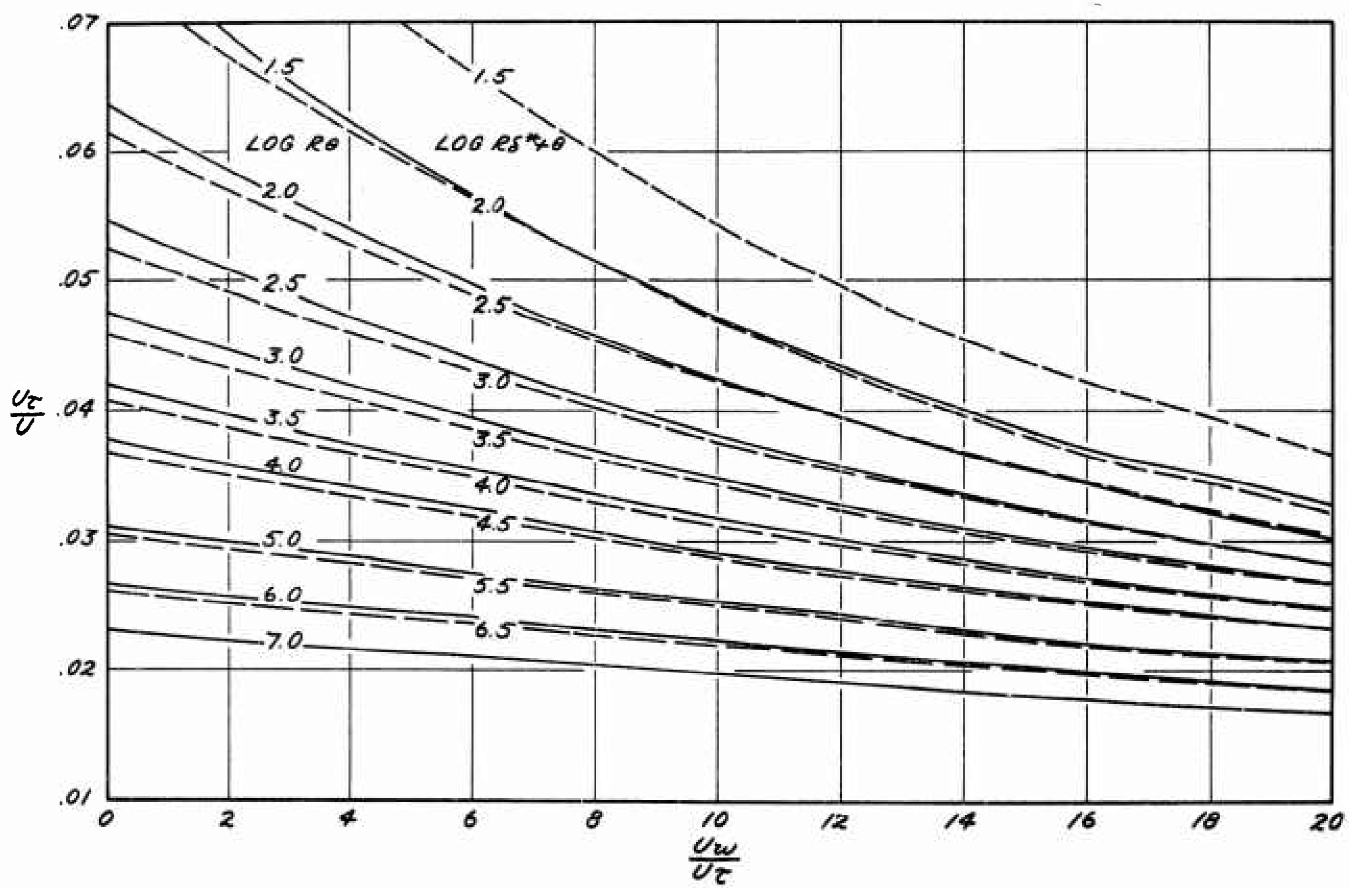

Figure 4. Chart of R_θ and $R_{\delta^* + \theta}$ Against $\frac{U_\tau}{U}$ and $\frac{U_w}{U_\tau}$.

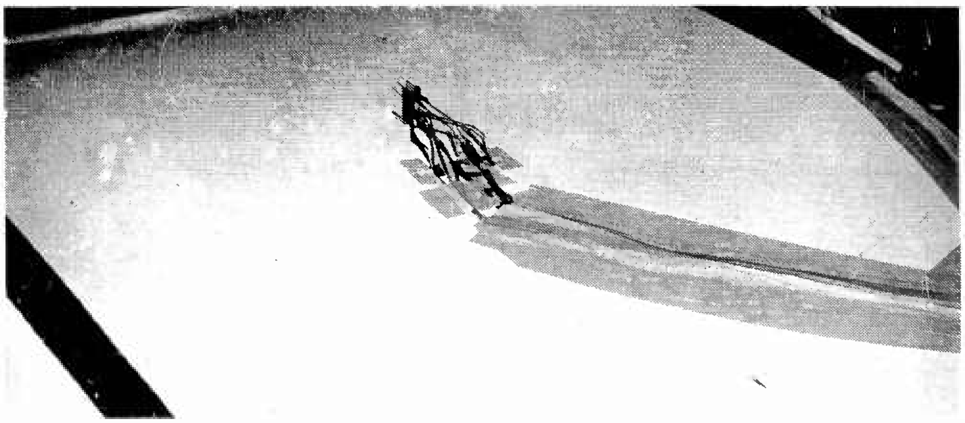

Figure 5. Composite Mouse on the Test Section.

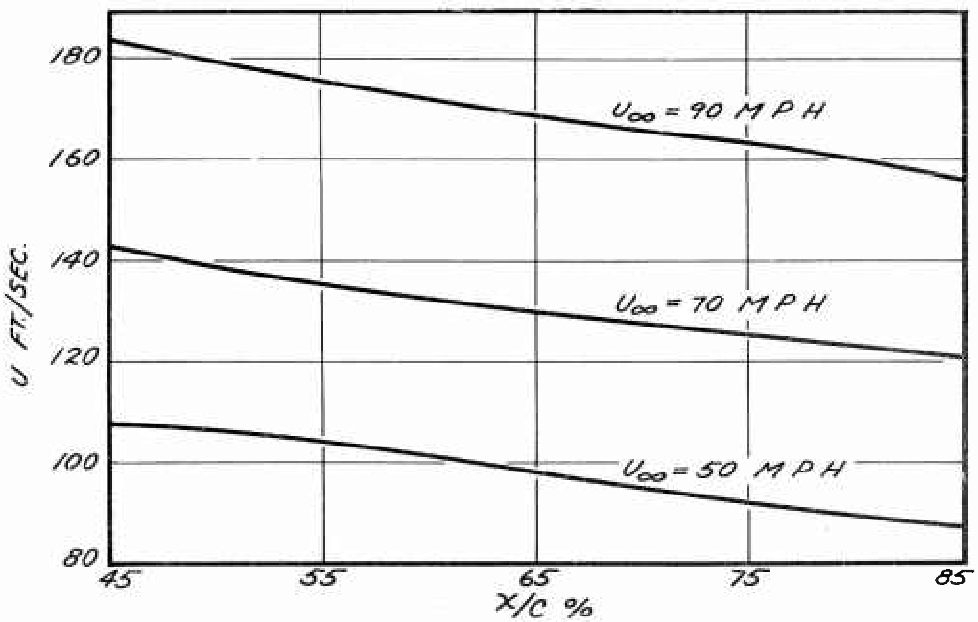

Figure 6. Velocity Distribution Over the Test Section.

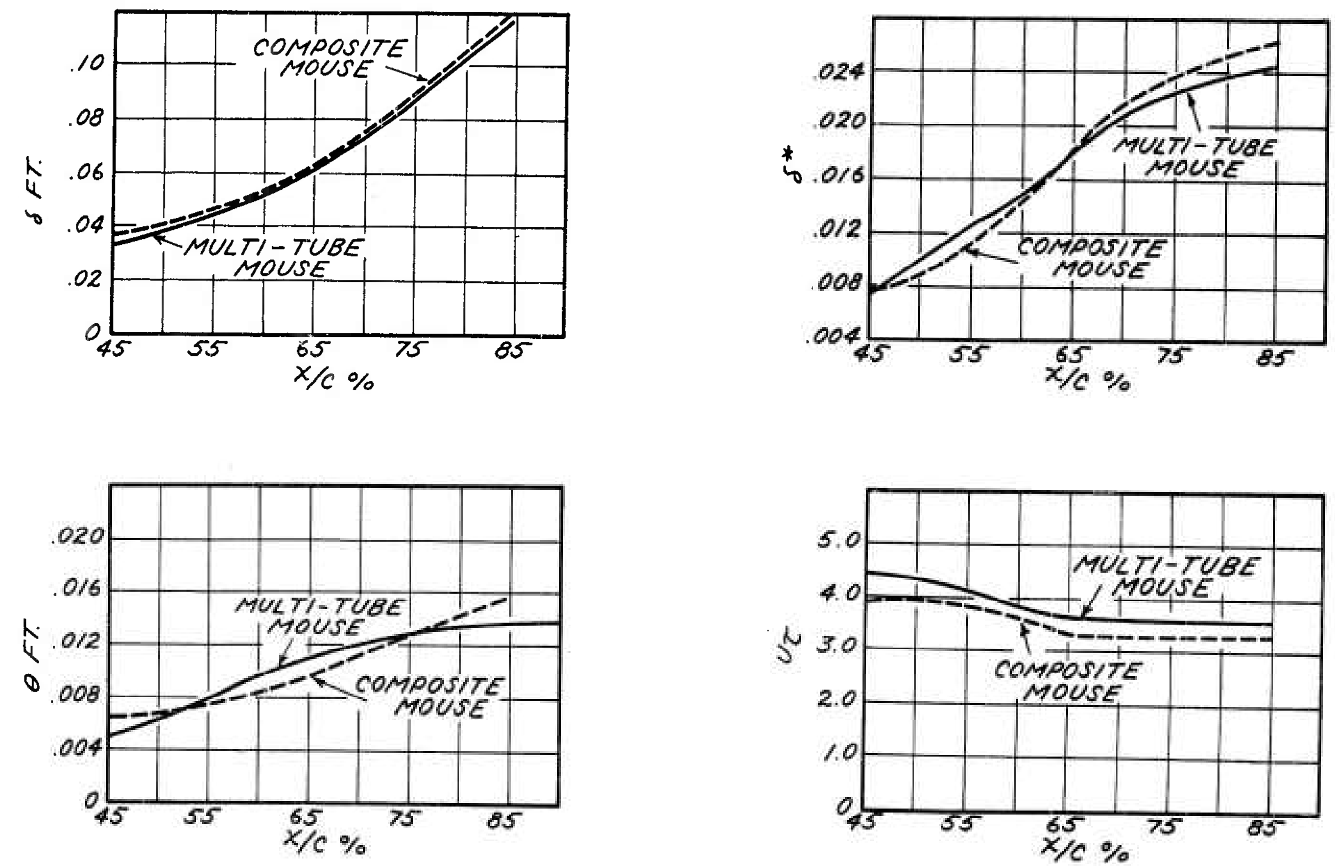

Figure 7. Comparison of Results From the Two Systems, U_∞ = 50 MPH, α = 10.5°.

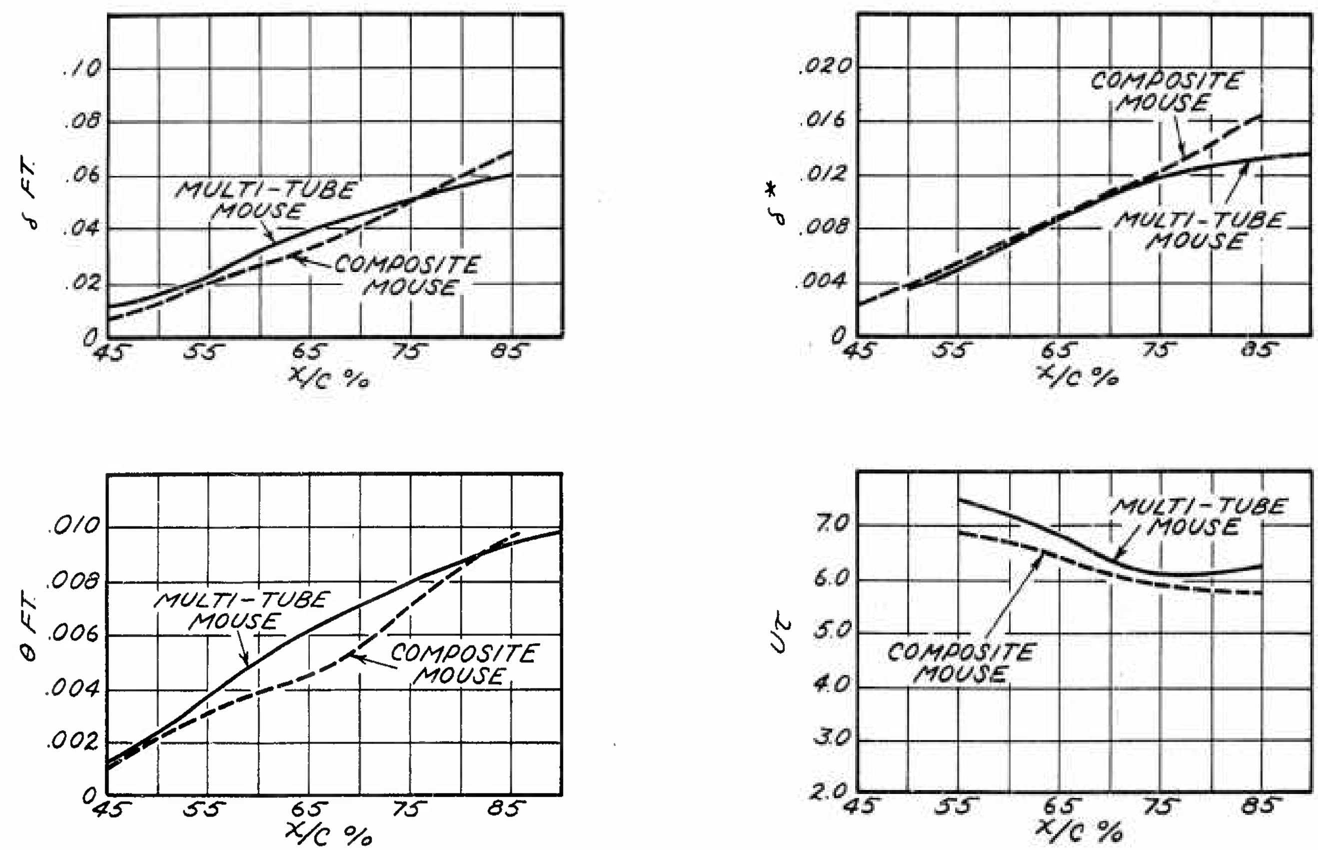

Figure 8. Comparison of Results From the Two Systems, U_∞ = 90 MPH, α = 2.0°.

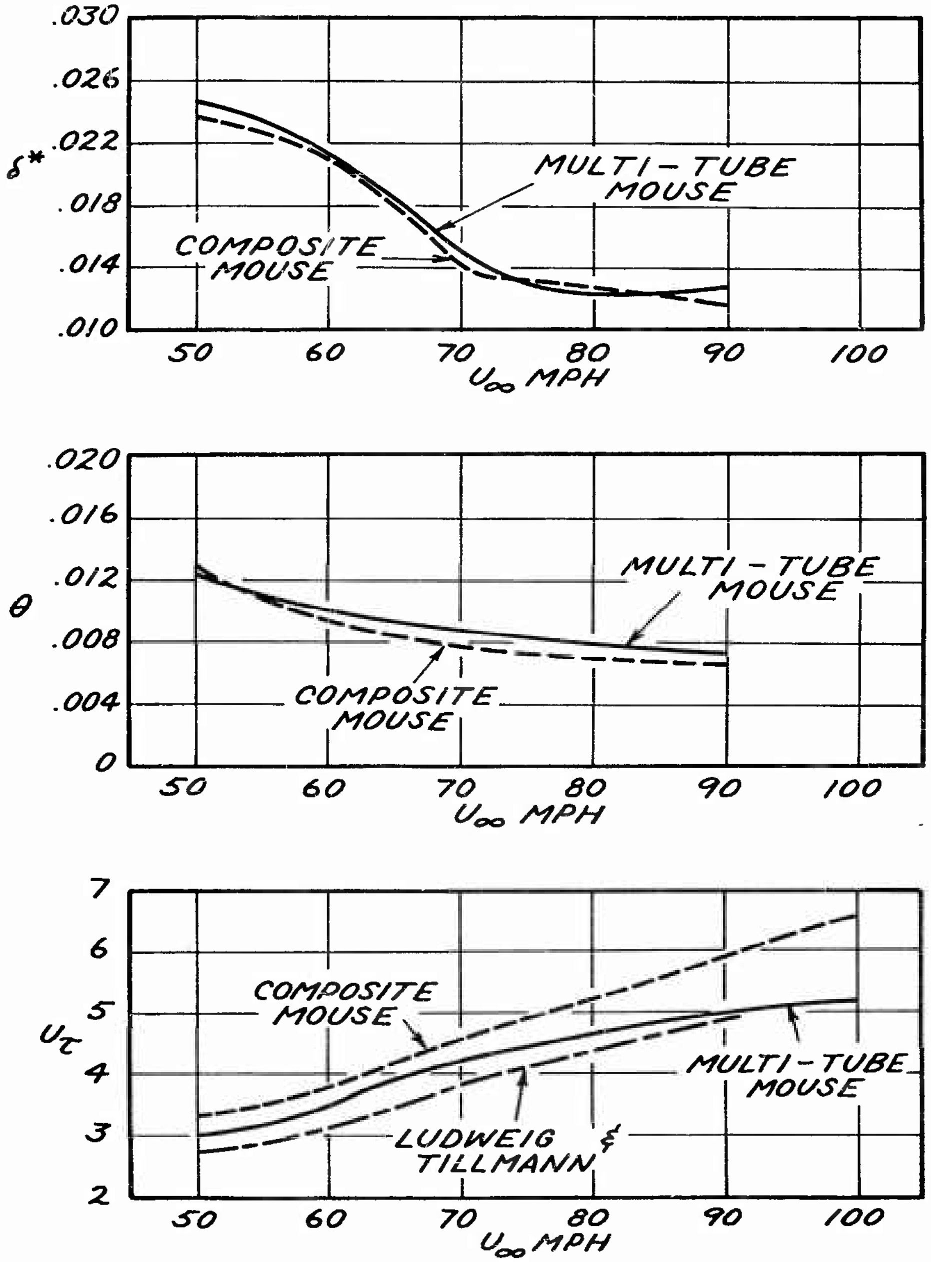

Figure 9. Comparison of Results at a Constant Chord Position, 75 Per Cent Chord.

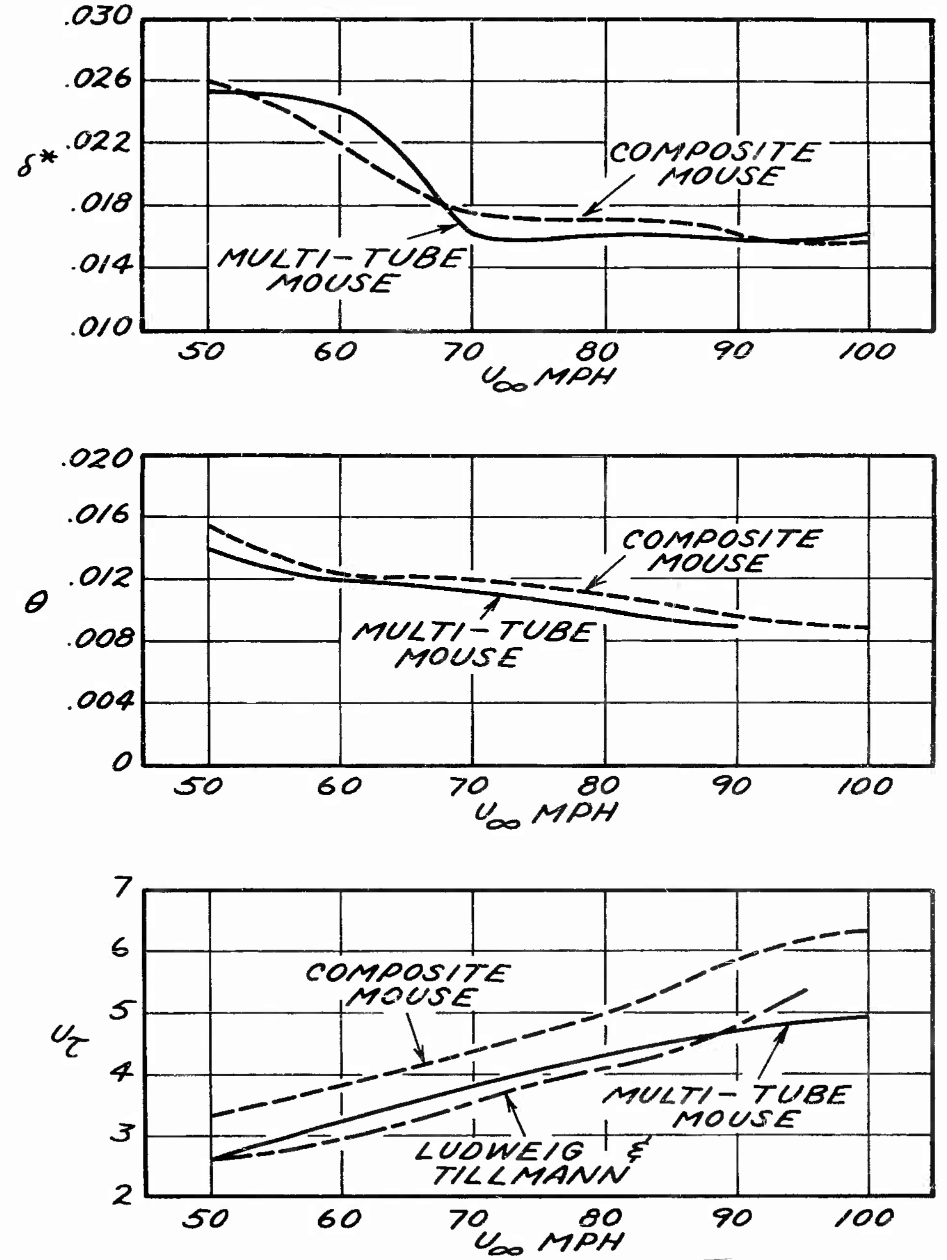

Figure 10. Comparison of Results at a Constant Chord Position, 85 Per Cent Chord.

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